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6. AUTHORS
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14. ABSTRACT
We have carried out preliminary work towards the construction of an optomechanical system that will reach the strong coupling regime. This system will consist of a millimeter-sized drop of liquid helium that is magnetically levitated in vacuum. The optical whispering gallery modes in this drop will serve as ultrahigh finesse optical cavities, while the drop's normal modes will serve as the mechanical elements. We have carried out the design of the levitation apparatus, and calculated several important aspects of the device's functionality.

15. SUBJECT TERMS
quantum optics, optomechanics, superfluids, magnetic levitation, optical cavities

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Jack Harris
					19b. TELEPHONE NUMBER: 203-432-3826

Report Title

Final Report: Ultralow Loss Optomechanics Using Diagmagnetically Levitated Drops of Liquid Helium

ABSTRACT

We have carried out preliminary work towards the construction of an optomechanical system that will reach the strong coupling regime. This system will consist of a millimeter-sized drop of liquid helium that is magnetically levitated in vacuum. The optical whispering gallery modes in this drop will serve as ultrahigh finesse optical cavities, while the drop's normal modes will serve as the mechanical elements. We have carried out the design of the levitation apparatus, and calculated several important aspects of the device's functionality.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

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Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

The work supported by this STIR has led to further support for this project from DARPA, the John Templeton Foundation, and the W. M. Keck Foundation.

REPORT OF INVENTIONS AND SUBCONTRACTS

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c. CONTRACT NUMBER: W911NF-13-1-0104

b. ADDRESS *(Include ZIP Code)*: 217 Prospect Street, New Haven CT, 06520

d. AWARD DATE *(YYYYMMDD)*: 20130415

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c. CONTRACT NUMBER:

b. ADDRESS *(Include ZIP Code)*:

d. AWARD DATE *(YYYYMMDD)*:

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a. FROM 20130415

b. TO 20140114

SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) *(Last, First, Middle Initial)* a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS (X) d. (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (X) e. (a) YES	e. (b) NO
None	None	None						

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR

(1) (a) NAME OF INVENTOR *(Last, First, Middle Initial)*

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(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*

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(b) NAME OF EMPLOYER

(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

(1) TITLE OF INVENTION

(2) FOREIGN COUNTRIES OF PATENT APPLICATION

SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME OF SUBCONTRACTOR(S) a.	ADDRESS *(Include ZIP Code)* b.	SUBCONTRACT NUMBER(S) c.	FAR "PATENT RIGHTS" d. (1) CLAUSE NUMBER	d. (2) DATE *(YYYYMM)*	DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e.	SUBCONTRACT DATES *(YYYYMMDD)* f. (1) AWARD	f. (2) ESTIMATED COMPLETION
None							

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a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL *(Last, First, Middle Initial)*: Harris, Jack, G. E.

b. TITLE: Associate Professor

c. SIGNATURE: Jack Harris

d. DATE SIGNED: 20150226

Final Technical Report for ARO Award #W911NF-13-1-0104 (15APR2013 – 14JAN2014)
"Ultralow loss optomechanics using diamagnetically levitated drops of liquid helium"

Jack Harris, *Departments of Physics and Applied Physics, Yale University, New Haven, CT*

The field of optomechanics focuses on coupling the electromagnetic degrees of freedom of a cavity to the mechanical degrees of freedom of a flexible object. When this coupling is strong enough that the quantum aspects of these degrees of freedom influence each other, scientific and technical goals spanning a wide range of topics can be realized. These goals include: quantum-limited detectors of force and displacement,[1] the production of nonclassical states of light and matter,[2] new architectures for quantum information processing,[3] and addressing fundamental questions about quantum effects in macroscopic objects.[4,5]

Progress in this field has been rapid; in the past two years, experiments have demonstrated ground state cooling,[6,7,8] entanglement with superconducting qubits, zero-point motion,[9] and quantum back-action.[10] Despite these dramatic results, the performance of optomechanical devices is still limited to a large degree by their optical and mechanical losses. Reducing these losses would immediately benefit nearly all of the goals in optomechanics, and is one of the outstanding technical challenges in this field.

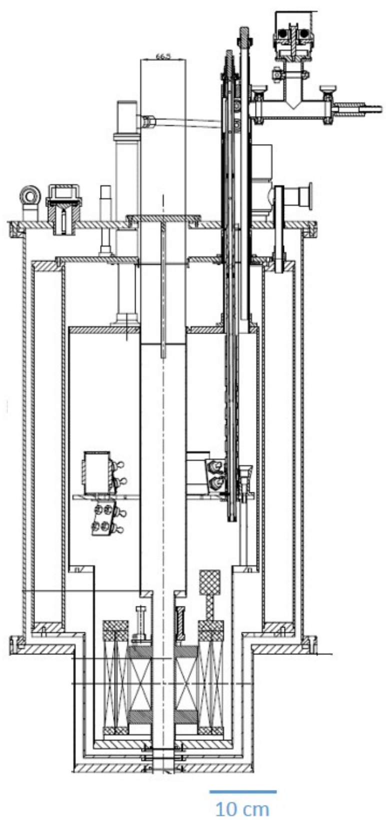

Fig. 1: Assembly drawing of the levitation magnet and cryostat ordered from Oxford Instruments. The magnet coils (crossed diagonal lines) enclose a bore that is a vacuum space, and can be accessed from room temperature. A similar magnet and cryostat was used in the previous demonstration of liquid helium levitation.[11,12,13]

The goal of this work proposed was to develop a new type of optomechanical device that would use the unique properties of superfluid liquid helium to achieve dramatically reduced optical and mechanical loss. Specifically, the goal was to use diamagnetic levitation to suspend a mm-scale drop of liquid He in vacuum so that the drop can serve both as an optical cavity (via its whispering gallery modes) and as a mechanical element (via its shape oscillations, rotation, and/or vortex motion).

In the nine month period of this work, we designed and commissioned a custom levitation magnet from American Magnetics, Inc. (Oak Ridge, TN). Upon testing, it was found that the magnet as produced did not meet specifications. AMI refunded our payments.

As a result, we have since collaborated with Oxford Instruments (Tubney Woods, UK) to develop a more robust design based on demonstrated performance in previous levitation experiments.[11,12,13] The assembly drawing of the magnet and its cryostat is shown in Fig. 1. It has been ordered and delivery is expected in June 2015.

At the same time, we have continued our theoretical investigations of levitated superfluid optomechanics. This work has been pursued in

close collaboration with the theory group of Florian Marquardt (Erlangen University, Germany). The Marquardt group's study of optomechanical effects associated with the drop's free rotation has been the subject of one Ph.D. thesis,[14] and is also being prepared for publication.

At present we are preparing the lab space for the delivery of the levitation magnet and cryostat. Although the necessary change in vendors has delayed our progress, we are still pursuing the goals outlined in our original proposal. Support for this ongoing work (i.e., after the end of the present STIR award) has been provided by DARPA and by private foundations.

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